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# AFRL BIODYNAMICS DATA BANK

## BIOLOGICAL PARAMETERS OF IMPACT

by

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## SOMMAIRE

Les progrés techniques des vols aériens et spatiaux, tels l'apparition des avions à grandes performances, des sièges éjectables, et, plus récemment, des fusées pilotées, ont stimulé l'étude des effets biologiques des accélérations brèves (impact). Les équipages aériens et spatiaux devant être soumis à des forces dynamiques brutales, il a fallu établir des critères utiles de tolérance pour déterminer les seuils de survie à l'impact. Dans ce but, on a eu recours à deux méthodes complémentaires: la définition de critères à partir des caractéristiques mécaniques et des réactions des membres d'équipage à l'impact, et l'évaluation de la réponse biologique à l'impact à l'aide d'observations physiologiques et cliniques.

Ces deux méthodes de recherche n'ont donné que peu de résultats objectifs. Etant donné le caractère complexe et hétérogène du corps humain, il n'existe pas de définition de ses caractéristiques physiques. Comme, d'autre part, les mathématiques, requises pour décrire correctement la réaction dynamique d'un modèle représentatif du corps humaine sont complexes, seuls les modèles les plus simples ont pu être étudiés. Bien que ceux-ci se soient révélés utiles au cours d'experiences réalisées sur de petits animaux, ils reposent sur l'hypothèse d'une défaillance possible due à l'élongation excessive d'une quelconque partie du corps, et il n'est pas encore prévu d'expériences sur l'homme basées sur ces critères de seuil. D'autre part, la diffusion biologique habituelle des données de cette nature exige que l'on procède à un grand nombre d'expériences pour établir la valeur statistique des résultats expérimentaux. Pour obtenir ces résultats, on procède à des expériences sur diverses espèces de petits animaux afin de déterminer la possibilité d'extrapolation des critères de tolérance entre espèces. On se propose de continuer ces recherches sur des animaux de plus grande taille de façon à pouvoir éventuellement, par extrapolation des résultats obtenus, déterminer les seuils de la tolérance humaine.

Les données biologiques à la fois objectives et obtenues dans des conditions expérimentales contrôlées sont également peu nombreuses. Les limites de tolérance actuelles ont été établies en se basant largement sur l'évaluation, par le sujet luimême, de la violence de l'impact, c'est à dire sur des critères que l'on qualifie habituellement de subjectifs. Ces évaluations ne peuvent avoir d'applications trés précises, mais elles sont complétées par l'observation médicale des signes et des symptômes qui apparaissent aprés le choc. Parmi les données cliniques utiles, on peut compter une vivacité de réflexes, des troubles visuels momentanés, une hypotension passagère conduisant à la syncope, des cas isolés de changements de conductivité affectant les phénomènes électriques cardiaques, ainsi qu'un ralentissement réflexe de la fréquence cardiaque. Des expériences récentes menées au 6571ème Laboratoire de Recherche Aéromédicale ont montré que ce changement de fréquence est de nature réflexe, probablement lié au sinus carotidien, et sous la dépendance des divers facteurs que sont la force, l'amplitude, la direction et la durée de l'impact.

# BIOLOGICAL PARAMETERS OF IMPACT

W.K. Brown, and R.F. Chandler

## INTRODUCTION

Investigation of the biological effects of abrupt acceleration (impact) was stimulated by the advent of technical advances in aerospace flight such as high performance aircraft, ejection seats and, later, manned rockets. Anticipated exposure to abrupt dynamic forces by aviation and space flight crew members necessitated the establishment of useful tolerance criteria as a means of predicting survival in the impact environment. Efforts directed toward this goal used two complementary approaches, i.e., the development of criteria based on the mechanical characteristics and response of the body to impact, and the biological response to impact evaluated in terms of clinical and physiological observations. A wealth of data pertaining to the injurious effects of abrupt acceleration is available from automotive and aircraft accidents. However, these data are of limited value in assessing limits of tolerance as concerns the operational situation. Analysis of accidental impact injury data is of greater benefit in arriving at an all-or-none criterion, i.e., survival vs non-survival.

In the operational environment of impact, one is vitally interested in that grey zone between no effect and gross injury or death. For example, the pilot who survives an aircraft crash, but who is injured or unconscious so that he cannot protect himself from secondary environmental conditions such as fire, would not consider survival a suitable tolerance limit for the impact.

## 2. MECHANICAL CHARACTERISTICS AND RESPONSE OF BODY TO IMPACT

Objective endpoints from both investigative approaches are noticeably few. In mechanical dynamics, it is well recognized that a mathematical model which represents the dynamic system is necessary to understand and describe the response of the system. However, the lack of definition of the physical characteristics of the complex and heterogeneous body, in addition to the complex mathematics necessary to adequately describe the dynamic reaction of a representative model, has enabled only the most simple models to be investigated.

The model frequently used in impact investigation is a simple spring-mass system. The major elements of the biological system are represented by equivalent mechanical elements in the model[9,10,11,12,13,14,15,16,17,21]. The various major elements of the body appear as lumped masses in the model, supported by springs and dashpots which

represent the force transmission system (skeletal) and energy dissipation system (soft tissue) of the body[3,4,7,8]. The model is subjected to an acceleration input and the response of the system used to predict the tolerance of the biological system to the acceleration input. However, in applying the mathematical model, and in biodynamic investigations in general, the definition of a suitable tolerance limit is unresolved.

Application of this technique has been used in two primary areas: (a) investigations with animals in comparative impact studies, and (b) the prediction of human tolerance using available data for criteria of survival tolerance. Both areas of investigation consider survival as the limit of tolerance. Application of model techniques to reversible physiological or biological alterations or to subjective evaluation as a tolerance limit has not yet been successful.

## 3. BIOLOGICAL RESPONSE TO IMPACT

Abrupt acceleration has frequently been considered as acceleration of brief duration in which biological responses are the result of mechanical forces acting primarily on the elastic and tensile properties of the tissues involved, and having little effect on physiological systems as the respiratory and cardiovascular[6,20]. Much of the early interest in this area centered around the development of restraint systems for the prevention of injury in crash impact and ejection from aircraft. Data obtained from centrifuge studies, in which the response to abrupt acceleration was limited by the rise time of prolonged radial acceleration, failed to reveal significant physiological effects.

Established limits of tolerance to impact forces were obtained by series of experiments using human subjects in which reversible injury was produced, and by isolated data points obtained from survivable crashes and falls[5,11,22]. Limits of reversible and irreversible injury were established in various animal species for selected impact environments. Correlation of human accidents with animal experiments provided the basis for extrapolating beyond experimental human tolerance limits. Wide variations in techniques of impact investigations, impact profiles (duration, magnitude and onset rate), and restraint systems, as well as the biological variations within and among individual animal and human subjects, have hindered the correlation of biological effects of abrupt acceleration.

With the advent of space flight, investigations of tolerance to abrupt acceleration achieved greater emphasis. Man would be exposed to predictable, controlled impacts of significant magnitude. Not only was there a need to know limits of tolerance to a wider variety of impact orientations of the body, but more precise and predictable criteria of tolerance were required.

Weis, et alii[24] exposed 20 human subjects in 75 experiments to six different impact profiles in seven different body orientations of pitch and yaw. The subjects tolerated exposure to impact in which velocity ranged from 4.82 to 8.47 m/sec, peak G from 13.3 to 26.6, onset from 386 to 1380 G/sec, and durations from 56 to 75 milliseconds. Biological effects were limited to one incidence of bradycardia (116 to 36 beats/min) and three instances of premature ventricular contractions. However, subjective reports and clinical evaluation of the subjects indicate that biologically untolerable limits were not reached.

## 4. IMPACT STUDIES AT HOLLOMAN

In a similar study conducted at Holloman Air Force Base, supported by the National Aeronautics and Space Administration, a total of 288 human impact tests were carried out using 24 different subject orientations with respect to the force vector[2,23]. Orientations were selected in 45° increments from the coronal plane of the subject and from anterior and posterior cones (90° included angle) with axes normal to the coronal plane (Fig.1). At each orientation, the impact force level was increased by increments of 2-5 G until a voluntary tolerance level was reached, based upon the occurrence of adverse subjective, clinical and physiological responses. The principal objective in this test series was to gather human response data which would furnish guidelines to be used in setting operational and emergency limits to space craft impacts. Frequent endpoint responses included persistent headaches, transient stunning and disorientation, transient visual disturbances as scotomata, and cardiovascular changes. The most significant physiological response was that of post-impact slowing of the heart rate (Fig.2). The change in heart rate represents the difference in the rate averaged over 20 seconds pre-impact and the rate averaged over the first 5 seconds following impact. Plotting change in heart rate versus the impact orientation, arranged in terms of resulting Z axis acceleration, a relationship between the magnitude of rate slowing and the degree of -Z axis orientation becomes apparent. The greater the resultant -Z axis vector, the greater the average slowing of the heart rate. This relationship is more evident in the 15.1 to 30.7 sled G range than in the lower range, although a similar trend exists. Typically, the rate decreases sharply at impact, then gradually returns to pre-impact levels over a period of 5-20 seconds (Fig.3).

Figure 4 illustrates the electrocardiographic evidence of rate slowing following impact. Slowing of the heart rate following abrupt acceleration has been demonstrated previously in man, but the relationship between the response and the direction of the force vector has not been clearly defined[1,18].

These findings led to a series of impact tests designed to study and compare the effects of $-G_z$ and $+G_z$ vector orientation. The acceleration pulse, which was constant for all tests, was trapeziodal in shape and sustained for 110 msec. The plateau force was 10G with an onset rate of 650 G/sec.

There is a marked decrease of 35 beats/min in the mean cardiac rate immediately post-impact in the $-G_z$ exposure. A slight increase in rate occurred in the $+G_z$ exposure, which was not significant. Within 20 seconds post-impact, the mean rates under both conditions approached the same value. Analysis of data indicates that the mean rate changes are significant (Tables 1, 2, 3).

The cardiac rate changes observed during these several investigations are consistent with the cardioinhibitory response of the carotid sinus pressoreceptors. It is hypothesized that a transient rise in hydrostatic pressure in the carotid arteries is produced by $-G_z$ abrupt acceleration, which in turn initiates the receptor response. The cardioinhibitory response is a function of the force vector magnitude and direction as well as the rate of force application.

Several other biological responses have been observed in human impact experiments. Measurements of maximum voluntary ventilation were made on 18 subjects exposed to 25G in $+G_x$ orientation. The pulse duration was approximately 60 msec and onset rate

was 1000 G/sec. Preliminary results suggest that maximum voluntary ventilation is increased immediately post-impact and then decreases from baseline levels within 10 minutes post-impact (Fig.6). Studies are currently underway to measure the effects of abrupt acceleration on pulmonary diffusion in man.

As an indicator of the general stress response to abrupt acceleration, the urinary excretion of catecholamines was measured in a group of subjects exposed to $+G_x$ acceleration at 20G with a duration of 60-70 msec and an onset of 1000 G/sec. In order to separate the effect of subject apprehension from that due to the impact, each subject received two tests on the deceleration device: one resulting in impact and a sham test in which the sled coasted to a stop short of the braking device. The subjects were not previously aware that a sham test would be performed. Figure 7 illustrates the catecholamine excretion (measured as vanilmandelic acid) in one subject at timed intervals before and after both test conditions. There is a continued increase in catecholamine excretion following impact as opposed to the return to the pre-impact levels following the sham test.

In summary, some of the problems in establishing useful tolerance criteria to abrupt acceleration, as well as the experimental approaches employed, have been presented. The successful application of model techniques to human tolerance prediction will be dependent upon advances in several areas. Present tolerance limits are based largely on evaluation of the severity of the impact in terms of subjective criteria. Biological data points which are objective and which were obtained under controlled experimental conditions are few in number. Recent experiments conducted at the 6571st Aeromedical Research Laboratory have demonstrated biological responses to abrupt acceleration which may be promising as tolerance indicators.

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## TABLE I

### Intra-experimental Comparison of Mean Cardiac Rates: Position $-G_z$

| | Pre-impact | | | Post-impact | | |
|---|---|---|---|---|---|---|
| Elapsed Time | T-20 | T-5 | T-5 | T+5 | T+5 | T+20 |
| Mean Cardiac Rate | 100 | 106 | 106 | 81 | 81 | 82 |
| $S\bar{X}_D$ (Standard error of the difference between Means) | 2.7 | | 2.9 | | 2.8 | |
| Probability of Difference | P < .05 | | P < .01 | | NS | |

## TABLE II

### Intra-experimental Comparison of Mean Cardiac Rates: Position $+G_z$

| | Pre-impact | | | Post-impact | | |
|---|---|---|---|---|---|---|
| Elapsed Time | T-20 | T-5 | T-5 | T+5 | T+5 | T+20 |
| Mean Cardiac Rate | 104 | 114 | 114 | 120 | 120 | 99 |
| $S\bar{X}_D$ | 1.9 | | 4.7 | | 3.0 | |
| Probability of Difference | P < .02 | | NS | | P < .01 | |

## TABLE III

### Inter-experimental Differences in Mean Heart Rates

| | Pre-impact | | | | Post-impact | | | |
|---|---|---|---|---|---|---|---|---|
| Elapsed Time | T-20 sec | | T-5 sec | | T+5 sec | | T+20 sec | |
| Subject Position | $-G_z$ | $+G_z$ | $-G_z$ | $+G_z$ | $-G_z$ | $+G_z$ | $-G_z$ | $+G_z$ |
| Mean Heart Rate | 100 | 104 | 106 | 114 | 81 | 120 | 82 | 99 |
| $S\bar{X}_D$ | 4.7 | | 4.9 | | 5.4 | | 5.5 | |
| $-G_z$ $+G_z$ | NS | | NS | | P < .01 | | P < .05 | |

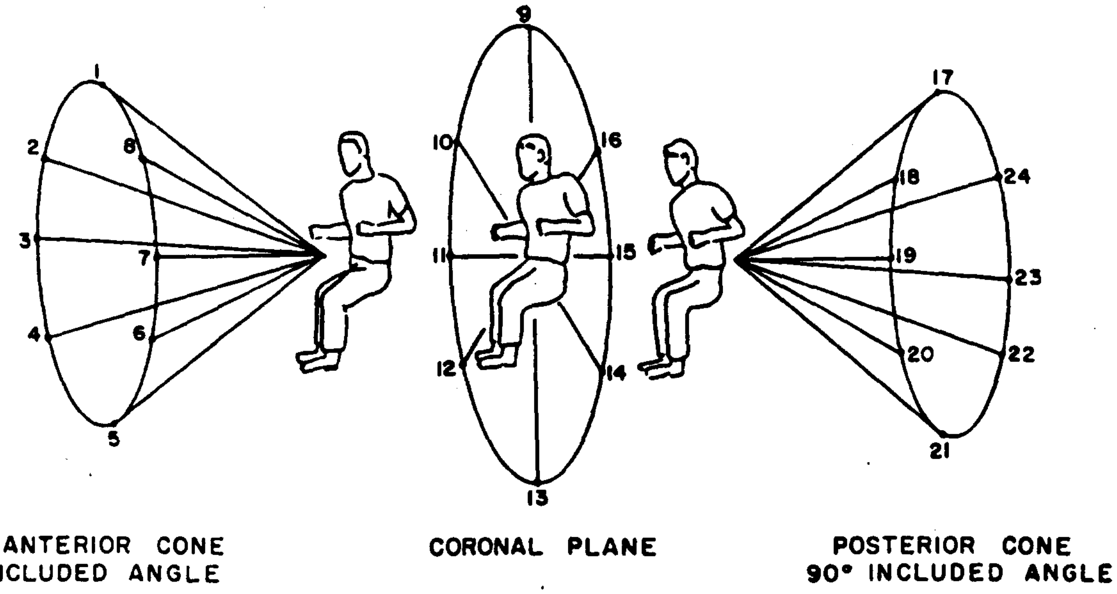


Fig. 1 Deceleration force vector orientations for human subjects. Each line represents a force vector with its corresponding numerical designation

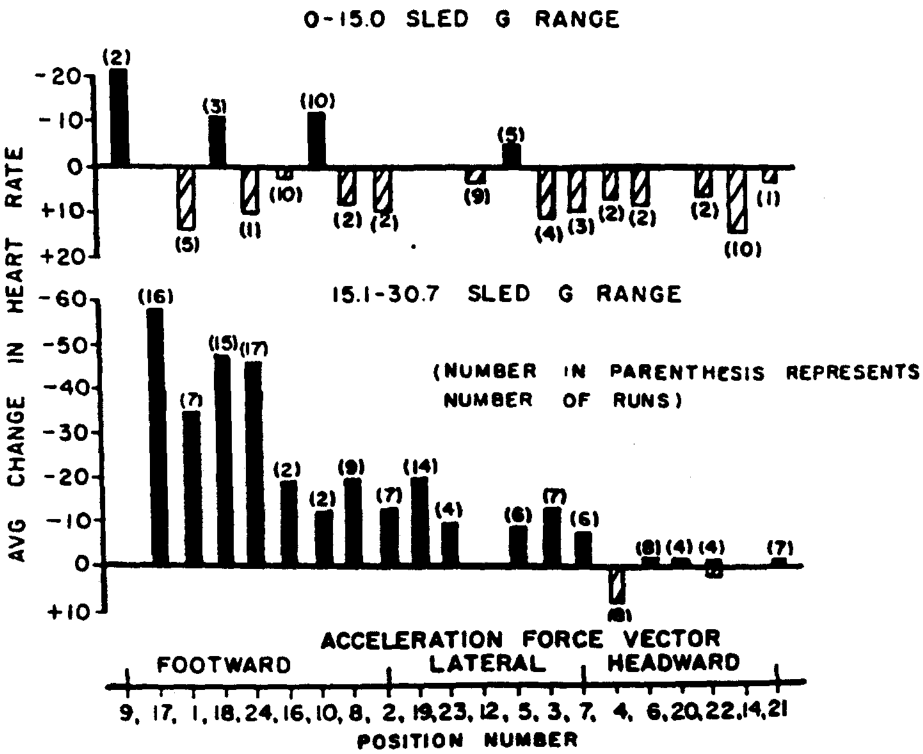


Fig. 2 Heart rate changes of human subjects exposed to abrupt acceleration up to 30.7 G in 21 different orientations. Impact orientations are ordered in degree of $\pm G_z$ acceleration resultant from transverse (lateral) axis

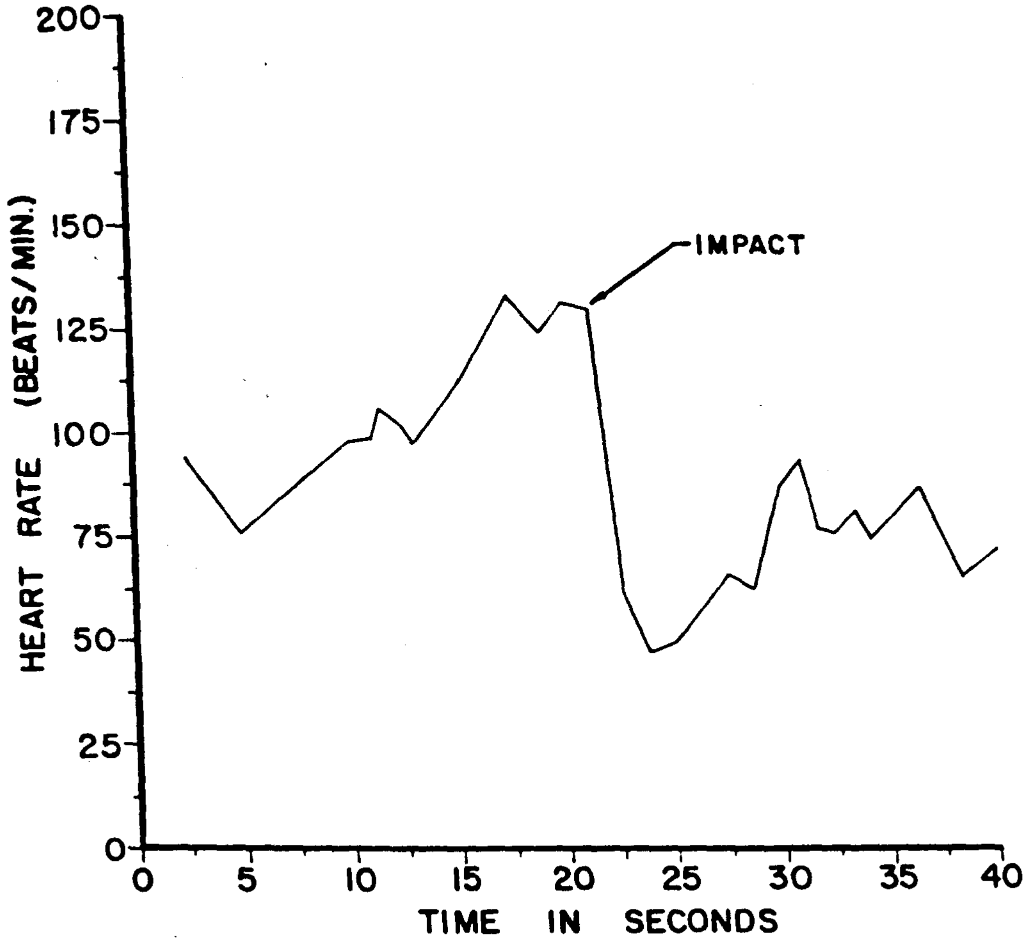


Fig. 3 Computer tracing of heart rate of one human subject before, during and following abrupt acceleration ($-G_z = 10$)

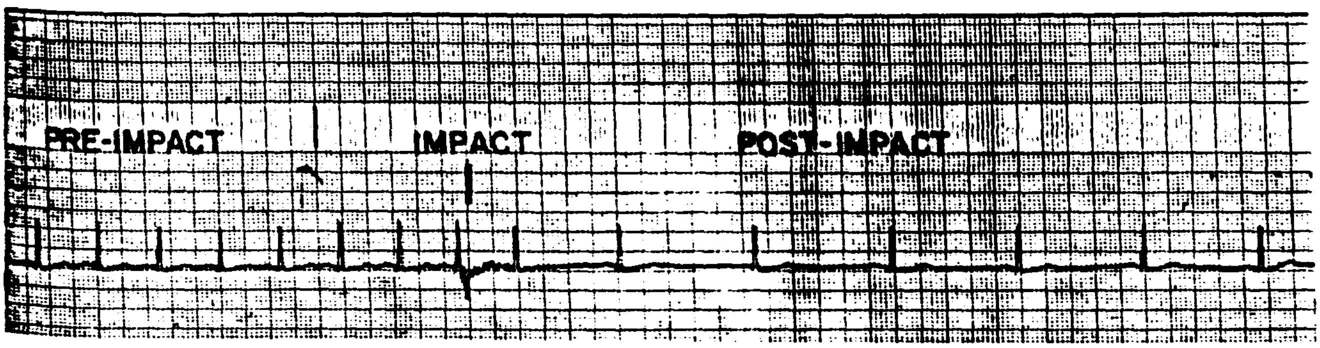


Fig. 4 Vector electrocardiogram lead X showing before, during and after impact tracing in $-G_z$ orientation. The Lead X positive electrode was positioned mid-sternum and the negative electrode over T-7 posteriorly. The recorder paper speed was 25 mm/sec

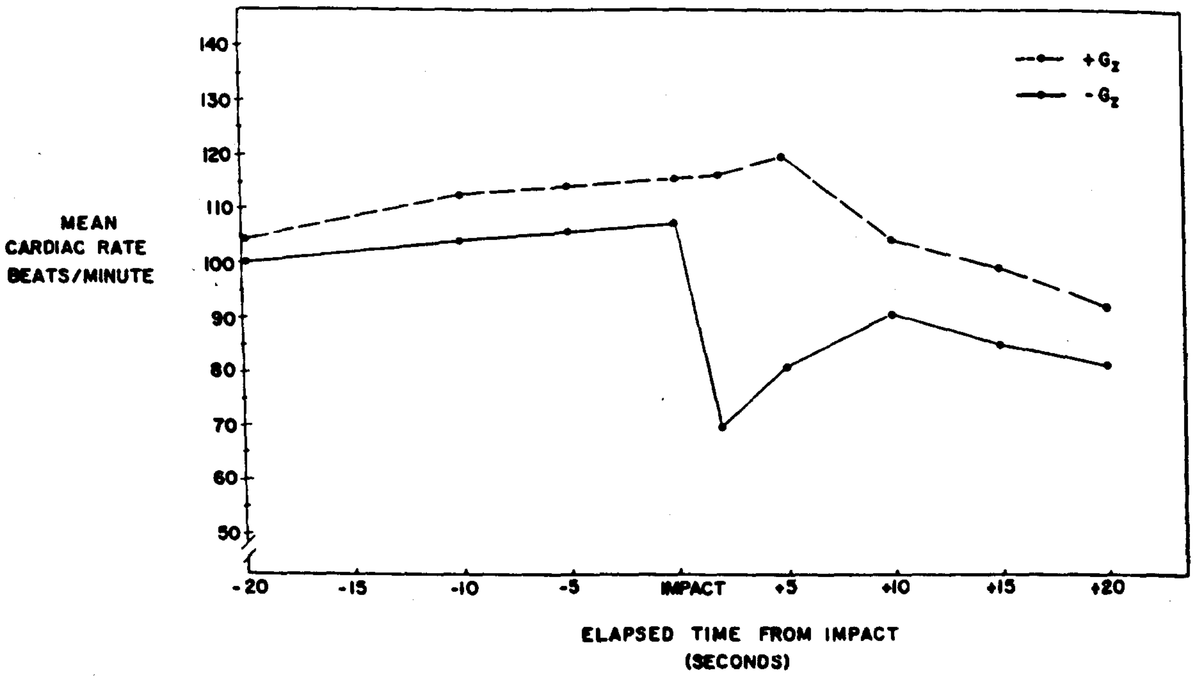


Fig. 5 Comparison of mean cardiac rate changes of 18 human subjects after abrupt acceleration in the $-G_z$ and $+G_z$ orientations

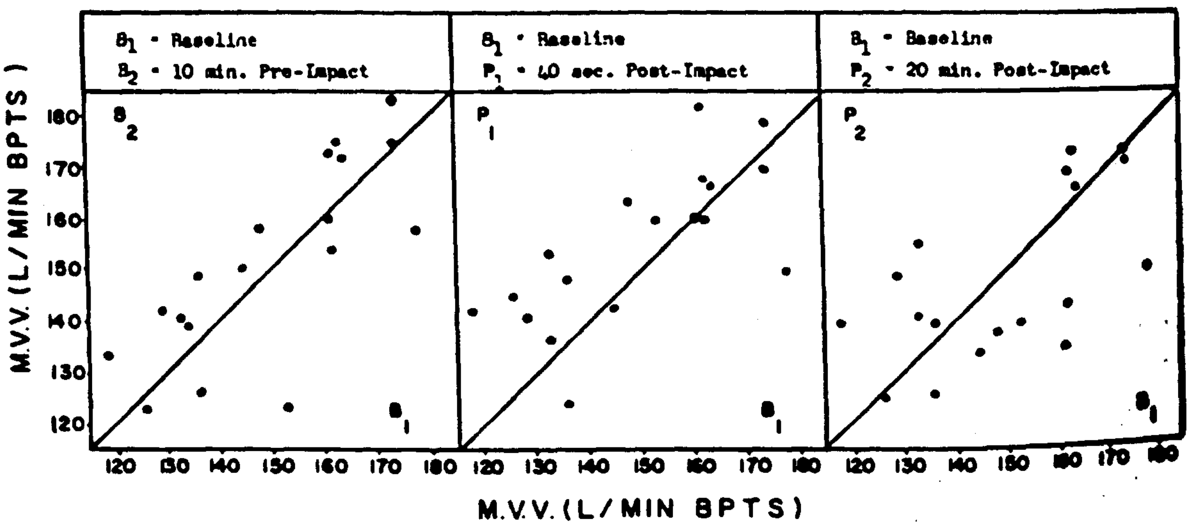


Fig. 6 Maximum voluntary ventilation in 18 human subjects. Comparison of baseline MVV with observations taken before and after abrupt acceleration

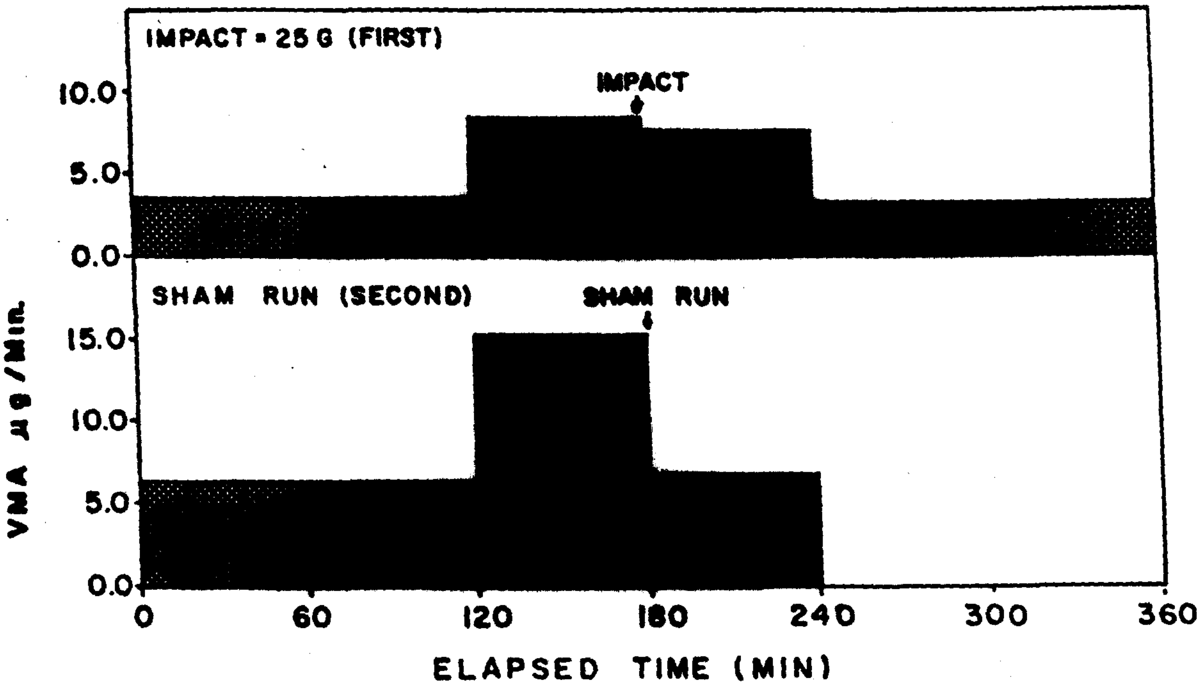


Fig. 7 Excretion of vanilmandelic acid (VMA) in urine of one human subject exposed to abrupt acceleration ($+G_x$ = 25) and during sham run. Sham run was conducted under identical conditions except that the sled coasted to a stop short of impacting the braking device. Timed urine samples were collected before and after the impact and sham tests